A High-Resolution Sensor Network for Monitoring Glacier Dynamics

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***Abstract*—This paper provides an overview of a wide area wireless sensor network that was deployed on the calving front of the Helheim Glacier in Greenland during the summer of 2013. The purpose of the network was to measure the flow rate of the glacier using accurate satellite positioning data. The challenge in this extreme environment was to collect data in real time at the calving edge of the glacier. This was achieved using a solar powered 2.4 GHz Zigbee wireless sensor network operated in a novel hybrid cellular/mesh access architecture consisting of ice nodes communicating with base stations placed on the rock adjacent to the glacier. This highly challenging transmission environment creates substantial signal outage conditions which were successfully mitigated by a radio network diversity scheme. The network development and measurement campaign were highly successful yielding significant results on glacial dynamics associated with climate change.**

***Index Terms*—PHEN, SYST, NET, WSN, GPS, extreme environment, glacial calving, Helheim, Greenland.**

I. Introduction

THE mass balance of the major ice sheets, and therefore their contribution to global sea-level rise, is controlled primarily by the speed of fast-flowing ice streams and outlet glaciers, terminating in ocean waters. During the early 2000s, there was a doubling of ice discharge in Greenland, which primarily resulted due to an increased flow rate of these tidewater glaciers [1] and it is possible that this phenomenon has been triggered by changes in the ocean waters at their calving margins [2]. However, accurately monitoring the flow rate of a glacier at its calving front is extremely challenging.

The project reported in this paper combined expertise in glaciology, Global Positioning System (GPS) technology and processing, and wireless networks to design, install and operate a wireless network of GPS sensors at the margin of the heavily crevassed Helheim Glacier in South East (SE) Greenland. Figures 1 and 2 illustrate the calving front of the Helheim Glacier and its catchment area[1], respectively. Moving at speeds of the order of 20 to 25 m/d, calving large icebergs along its 6 km calving front, the glacier is a major outlet of the SE Greenland ice sheet making it a challenging environment to monitor [5]. From lessons learned through the deployment of a small-scale field trial network in July 2012, a scaled up network consisting of 20 GPS nodes was deployed on the glacier during the summer of 2013. The on glacier ice nodes provide full code and phase dual frequency GPS data every few seconds to base stations positioned on rock at the edge of the glacier. Of the 20 ice nodes deployed, 19 communicated successfully with the network base stations. High resolution position data available from the high temporal sampling means calving events can be monitored to the point of sensor loss, differentiating the real time capability of the network from previous solutions.

Fig. 1: Calving front of Helheim Glacier.

II. Literature Review

The work reported in this paper focusses on the deployment of a wireless sensor network in an extreme environment close to the calving front of the Helheim Glacier which is Greenland's third-largest outlet glacier. The glacier surface consists of crevasses and parallel fissures up to 30 m deep and mounds of ice which may be up to 10 m above the local surface height of the glacier. Figure 1 illustrates the Helheim Glacier draining from the Greenland ice-sheet with the calving front and ice mélange (i.e. calved blocks of glacial ice), in the foreground. Such a remote and hostile terrain makes human observation platforms difficult and glacier observation is often conducted using satellite imagery. This, however, limits the information flow rate to at most 1 sample per 10 days. Given that the flow rate of the ice streams greatly exceed this resolution, surface flow measurements using GPS data are attractive. Dual frequency GPS equipment can provide positional data every second with an accuracy of 1-2 cm in plan and 2-5 cm in vertical whereas single frequency GPS equipment

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[1]Balance Velocity - Created at the University of Montana by Jesse Johnson in July 2009.

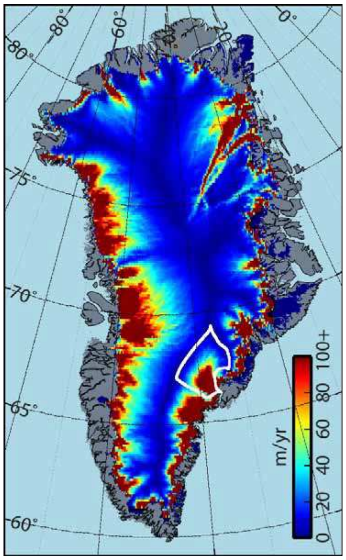

Fig. 2: Helheim catchment location in Greenland (white boundary shows catchment area). Background image is balance velocity.

can exhibit positional accuracy of several tens of metres. Reference [3] provides a review of remote sensing techniques employed in glaciology studies. In particular, the value of GPS in determining glacier surface velocity is discussed.

Previous significant research on monitoring the surface velocity of a tidewater glacier in Greenland using GPS sensor nodes is reported in [2], [4]. The research team successfully operated a network of continuously recording GPS receivers on the Helheim Glacier for periods of 54 and 55 days during the summers of 2007 and 2008, respectively. In the field trial of 2007, a total of twelve GPS receivers were deployed on the glacier. The majority of nodes were deployed along the glacier's central flow line spanning a total distance of 20 km. A small number of nodes were deployed offset from the centreline while a few nodes were positioned immediately behind the calving front. In the 2008 field trial, 22 nodes were deployed again focussing on the major flow lines of the glacier but not extending to the calving front. In both field seasons some GPS receivers were positioned on rock sites next to the glacier in order to provide stable local GPS reference frames. Results on glacier velocity were obtained using a 15 s sampling interval.

In contrast, the research reported in this paper focusses on the deployment of a wide-area wireless sensor network of 20 GPS nodes immediately behind the calving front of the Helheim Glacier. Using a sampling interval of $\sim$ 7 s, the network provided near real time positioning information which can be translated into high resolution spatial and temporal information about the dynamic behaviour of the glacier at the calving front. The wireless network used commercial off the shelf (COTS) 2.4 GHz Zigbee technology and purpose build antennas to achieve reliable communication over such a hostile environment. The network was deployed for 50 days during the summer of 2013.

III. NETWORK EQUIPMENT

The network consisted of 20 on-ice GPS receiver nodes and 4 logging base stations placed on the rock at the side of the glacier. Zigbee transceivers operating in the 2.4 GHz ISM band are used to transmit the GPS data from the ice nodes to the loggers. Zigbee transceivers are designed for the hostile radio frequency (RF) environments and provide a low-power, low-cost wireless network with automatic retries and automatic network formation [6]. The whole network is powered by solar panels with backup batteries to span cloudy days and night time. Base stations act as Zigbee network coordinators and collect data from nodes. Figure 3 illustrates a logging base station whereas Figure 4 illustrates an ice node. To achieve high temporal sampling rates, $\sim$ 7 s for each ice node, the network was divided into 4 sub-networks of 5 nodes each operating simultaneously. Typically, Zigbee uses carrier sense multiple access (CSMA) in order to avoid transmission collisions. However, on the glacier this functionality is severely restricted because the crevassed surface shields the ice nodes from each other giving rise to the hidden terminal problem. Therefore, RF collisions within a subnetwork are avoided by employing a base station round robin scheme that polls each ice node for a message to which it replies with GPS data. Nonetheless, the network was configured to support at least two hops. Thus on occasions when data could not be returned to the base stations in a single hop, the possibility existed for a node to send its data to the base station via at least one other ice node.

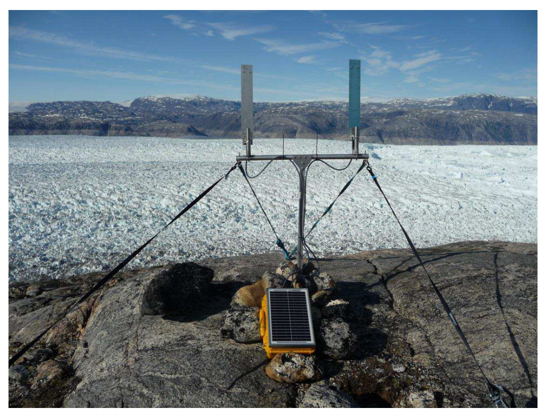

Fig. 3: Logging base station.

IV. RADIO DIVERSITY

To provide wireless diversity each ice node contains two independent Zigbee transceivers linked through an RF 3dB splitter to an omnidirectional antenna with a 3dBi gain. A schematic of the ice node hardware is shown in Figure 5. The two transceivers communicate with different base stations providing two radio routes off the ice. For the 20 node network this leads to 8 subnetworks each operating in a different frequency band.

Figure 6 shows the nominal network layout and allocation of the Zigbee channels to the 8 subnetworks. The hexagons represent ice nodes coloured according to the frequency allocation chart whereas base stations are denoted by coloured

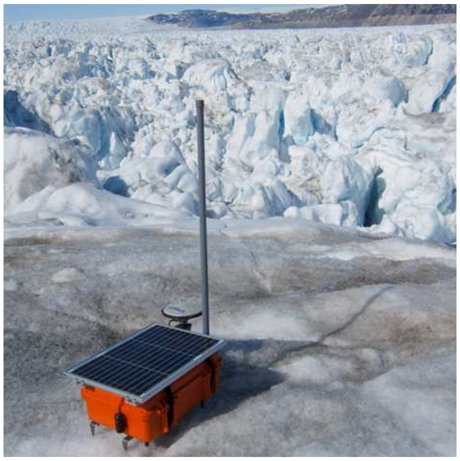

Fig. 4: Ice node.

squares. The green dashed lines show the beam width (at least 90°) of the 12dBi high gain base station antennas [7]. The channel allocation is chosen to maximise the frequency separation between collocated transceivers at both the nodes and the base stations to reduce adjacent channel interference. The network is split into North and South segments due to the very large scale of the glacier topography. With a maximum Zigbee transmit power of just 50 mW, 12 dBi antenna gain at the base station and 3 dBi antenna gain at the ice node, the network was designed to give radio coverage across the full 6 km width of the glacier [8].

Figure 7 shows successful GPS data reception at the base stations for each ice node. Vertical grey shaded bars shows time periods of extensive calving activity. Visible data gaps at one base station but spanned by the other, demonstrate uplink diversity. Figure 8 shows the received signal strength from ice node 3 at the North East (NE) and North West (NW) base stations. Care taken on node deployment ensured that the initial received signal strength indicator (RSSI) was substantially above the hardware RSSI limit of -102 dBm.

Despite the node to base station range changing slowly, there are large changes in received signal strength at times dropping below the operational threshold of -102 dBm. This is due to the obstructions and multipath interference caused

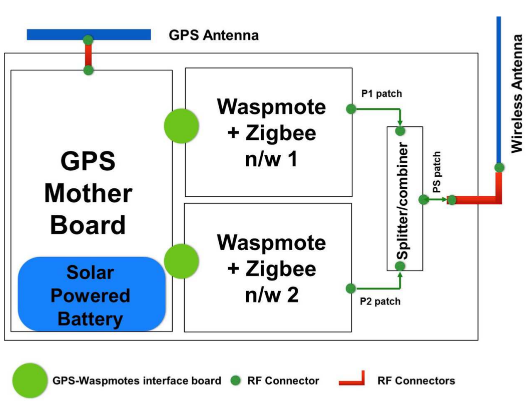

Fig. 5: Ice node subsystem diagram.

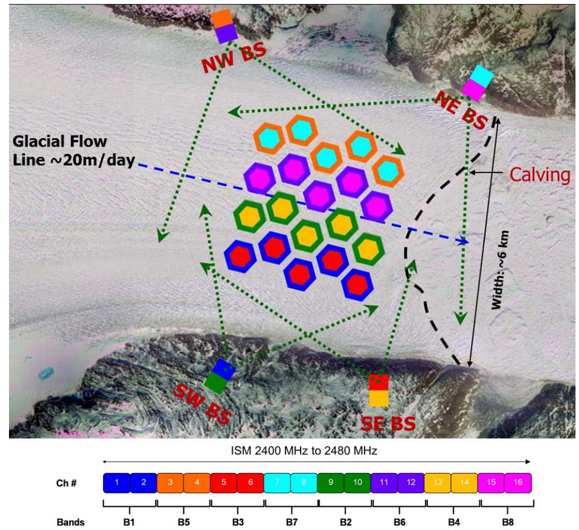

Fig. 6: Wireless network layout and frequency allocation.

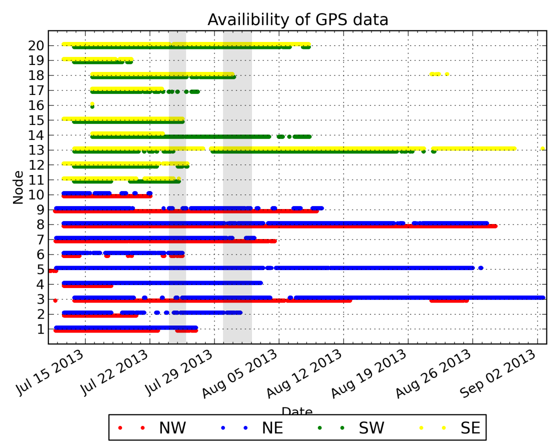

Fig. 7: GPS data profile over trial period.

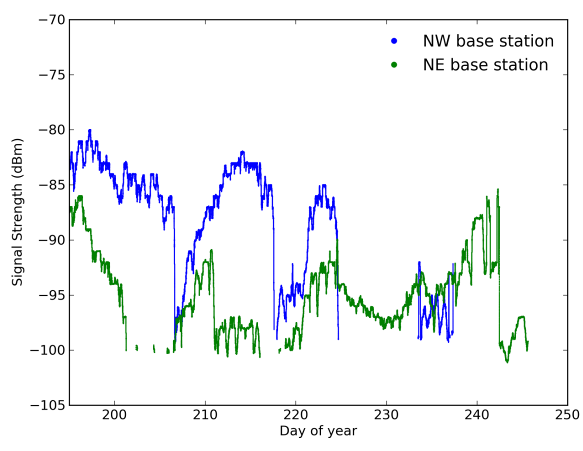

Fig. 8: RSSI at ice node 3.

by the complex local environment - see Figure 4. The average RSSI agrees within ±3 dB of values obtained by modelling the environment [7]. Combining the data collected at the two base stations for this particular node covers the complete deployment period from mid July to the end of August 2013.

V. GPS RESULTS

Over 7 million epochs of raw GPS observation data were recorded during the 2013 field season. The observation intervals for each ice node was in the range 4 to 8 seconds. Ice node positions have been estimated using Track (GAMIT v10.5) carrier phase relative positioning software. The GPS reference site was the NW base station. Processing was performed using the ionosophere free linear combination and CODE final orbits/clocks. Tropospheric zenith delay was modelled [9] and mapped to satellite elevation using the GMF [10], [11]. The Zenith wet tropospheric correction was not estimated due to the positional degradation it causes during periods of low satellite visibility. The ice node position was estimated at each epoch using a Kalman filter process noise of 1 cm/s to ensure capture of calving dynamics. Formal errors are between 1-2 cm in plan and 2-5 cm in vertical. This allows detection and isolation of tidal signals in the position time series which is useful to future data analysis.

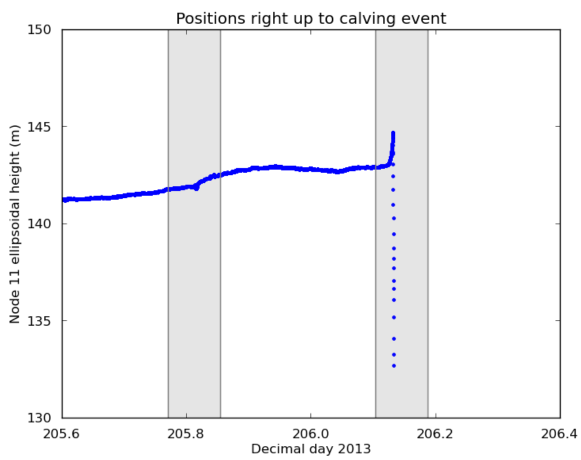

Fig. 9: Node 11 height profile showing node loss at the calving front.

Figure 9 demonstrates the high resolving power of the network right up to the time of the loss of a node. In Figure 9, the grey shaded vertical bars correspond to time periods of calving activity with node 11 being lost during a calving event at approximately 206.14 decimal days. These data provide valuable information about the glacier at the time of calving not previously measured [2]. The data will allow the authors to investigate fundamental questions such as: the detailed mechanics and dynamics of glacial calving; the significance of surface water in calving; and the relationship between the tides and calving events [12], [13].

VI. CONCLUSION

A robust wireless network of GPS sensors has been designed and successfully operated at the active calving front of the marine outlet, Helheim Glacier. Wireless diversity of the network data backhaul has yielded >7 million observations in a single field season. Network tracking to the point of node loss has been demonstrated. GPS data processing provides formal errors between 1 to 2 cm (plan) and 2 to 5 cm (vertical), allowing detailed evaluation of the glacier dynamics at the calving front. GPS data obtained is one component of a unique and rich data set including >6000 oblique stereo-photographs and 1.2 TB of airborne data. The wireless network design proved to be highly robust in such an extreme environment and future applications such as volcano and landslide monitoring are currently being considered.

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